

Forage Radish Cover Crops Increase Soil Test Phosphorus Surrounding Radish Taproot Holes

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Cover crops can influence nutrient cycling in the agroecosystem. Forage radish (FR) (*Raphanus sativus* L. var. *longipinnatus*) is unique in terms of P cycling because of its high tissue P concentration, rapid growth in the fall, and rapid decomposition in winter and spring. In addition, FR produces a taproot that decays during the winter and leaves distinct holes in the surface soil. This study measured P uptake by FR and cereal rye (CR) (*Secale cereale* L.) cover crops; the Mehlich 3 P concentration (M3P) in bulk soil following FR, CR, and no cover crop (NC); and M3P in soil within 3 cm of FR taproot holes. Cover crop treatments of FR, CR, and NC were established at two sites each fall for three subsequent years in a cover crop–corn (*Zea mays* L.) silage rotation. Cover crop shoot P uptake ranged from 5.9 to 25 kg P ha⁻¹ for FR measured in the fall and from 3.0 to 26 kg P ha⁻¹ for CR measured in the spring. The greatest cover crop effect on bulk soil M3P was observed at the 0- to 2.5-cm depth after 3 yr of cover crops, with M3P values of 101, 82, and 79 mg P kg⁻¹ after FR, CR, and NC, respectively. Soil within 3 cm of FR taproot holes had greater M3P than FR and NC bulk soil. Further studies should be conducted to determine if FR could increase P removal rates in excessively high P soils or increase P availability in low P soils.

Abbreviations: BARC-SF, Beltsville Agricultural Research Center South Farm; CMREC, Central Maryland Research and Education Center.

Forage radish is being used in many parts of the world as a winter cover crop to alleviate soil compaction, reduce NO₃ leaching, suppress weeds, and control erosion (Weil and Kremen, 2007). In the Mid-Atlantic United States, forage radish is being used by an increasing number of dairy farmers as a cover crop between corn silage crops. Among the many unique characteristics of forage radish are its relatively high tissue P concentration, rapid dry matter accumulation in the fall, and rapid residue decomposition in the spring. In addition, the forage radish produces a large fleshy taproot, typically 3 to 6 cm in diameter and 15 to 30 cm in length (Fig. 1). This fleshy taproot decays during the winter to leave distinct holes in the surface soil that may enhance infiltration and reduce runoff in the spring. The root holes left after the forage radish taproots decompose are often 3 to 6 cm in diameter and 5 to 10 cm deep. These characteristics of forage radish cover crops present several potential opportunities and challenges for P management in the agroecosystem, including remediation of excessively high P soil, increased concentration of P at the soil surface, and improved fertility of low P soil.

Agricultural soils that are excessively high in P are common in the developed world and P transport from these soils to natural waters is one of the primary causes of eutrophication (Boesch et al., 2001; Sharpley et al., 2001). The concentration of P in soils can be reduced with time by eliminating the use of fertilizers containing P while continuing to remove P from the soil through harvested crops (Brown, 2006; Eghball et al., 2003). Cover crops may be harvested to feed to livestock directly as green chop or to make silage (Kratovich et al., 2006). Harvesting a cover crop such as forage radish in addition to the main crops in a rotation could increase the

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Fig. 1. Forage radish taproots typically measure 3 to 6 cm in diameter and 15 to 30 cm in length (left). Recommended planting rates result in approximately 80 plants per square meter. Forage radish winterkills and the shoots and roots decompose quickly, leaving distinct taproot holes (right) in the soil surface in spring. Scale in inches and centimeters.

amount of P removed from the soil each year, resulting in faster remediation of the soil to environmentally safe P levels.

Allowing cover crop residues to decompose at the soil surface, as opposed to harvesting the cover crops as described above, is a more common practice in no-till agriculture. Decomposition of cover crop residues on the soil surface may lead to an accumulation of P at the soil surface where it is susceptible to losses by runoff and erosion. In continuous no-till agriculture, soils commonly develop high P concentrations at the surface because crop residues and fertilizers are applied to the soil surface and P is relatively immobile in soil (Duiker and Beegle, 2006; Garcia et al., 2007; Sharpley, 2003; Weil et al., 1988). Cover crops that accumulate large quantities of P in their shoots may accentuate the stratification of soil P when managed with no-till practices.

Increasing the plant availability of soil P via biologically based mechanisms has been studied as a means of improving soil fertility, especially when soluble P fertilizers are not accessible to farmers. Members of the Brassicaceae plant family can solubilize recalcitrant forms of soil P by changing the rhizosphere pH (Grinstead et al., 1982; Hedley et al., 1982; Hinsinger and Gilkes, 1997; Marschner et al., 2007) and exuding organic acids (Hoffland et al., 1989; Shahbaz et al., 2006; Zhang et al., 1997). Rotations or intercrops of *Brassica* species, however, have shown little effect in improving P uptake by the companion or subsequent crop (Wang et al., 2007; Weil, 2000). When Brassicaceae members are grown as a cash crop or as an intercrop, the soil P mobilized by the Brassicaceae crop is removed at harvest or sequestered in plant tissue. A Brassicaceae green manure or cover crop that is not harvested but is instead returned to the soil to decompose may be more effective in improving subsequent P

availability because the P mobilized by the Brassicaceae crop would be cycled back into the soil instead of being removed at harvest. Cavigelli and Thien (2003) found that P uptake of a sorghum [*Sorghum bicolor* (L.) Moench] crop was positively correlated to the P uptake of a previous green manure crop. In low-P soil, Brassicaceae species may prove advantageous as green manure crops due to their ability to take up greater quantities of P from the soil.

Other cover crops or green manures besides Brassicaceae members may also increase P availability. Bah et al. (2006, 2003) found that green manures of two legume and one grass species increased P availability in an Ultisol, and Reddy et al. (2005) found that incorporation of soybean [*Glycine max* (L.) Merr.] and wheat (*Triticum*

aestivum L.) residues increased P availability in an Alfisol. In both cases, increases in P availability were attributed to a reduction in soil P sorption capacity because organic decomposition products from the green manures filled P sorption sites in the soil.

There have already been reports of increased soil test P following forage radish cover crops. Forage radish slightly increased soil test P compared with three other Brassicaceae cover crops and a sorghum–sudangrass [*Sorghum bicolor* (L.) Moench × *S. sudanese* (Piper) Stapf] cover crop at the 0- to 15-cm depth range (Wang et al., 2008). In a study reported by Grove et al. (2007), soil test P increased in the 0- to 45-cm depth range following 3 yr of forage radish cover crops compared with treatments of rape (*Brassica napus* L.), cereal rye, and no cover crop.

This study had two objectives: (i) to measure P concentration and P quantity in the tissue of forage radish and rye cover crops; and (ii) to determine the effect of forage radish and rye cover crops on soil test P in bulk soil at different soil depths and in the soil immediately surrounding the holes created by forage radish taproots.

MATERIALS AND METHODS

Experimental Design

Experiments were conducted at the University of Maryland Central Maryland Research and Education Center (CMREC), and the USDA Beltsville Agricultural Research Center South Farm (BARC-SF). The experiments started in August 2006 and ended in May 2009. Site and soil properties are listed in Table 1.

In all site years, a randomized complete block experimental design with four replicates was used with three cover crop treatments: forage radish (seed source: Steve Groff Seeds, Holtwood, PA), cereal rye (cv. Wheeler), and no cover crop. The no-cover-crop treatment was

Table 1. Selected characteristics and soil properties of the University of Maryland Central Maryland Research and Education Center (CMREC) and the USDA Beltsville Agricultural Research Center South Farm (BARC-SF) experimental sites.

	CMREC	BARC-SF
Location	Greenbelt, MD	Beltsville, MD
Latitude	39°0'42" N	39°2'1" N
Longitude	76°49'54" W	76°55'53" W
Hectares	0.57	0.93
Slope, %	4	0.5
Soil series	Downer	Codorus
Taxonomic classification	coarse-loamy, siliceous, semiactive, mesic Typic Hapludult	fine-loamy, mixed, active, mesic Fluvaquentic Dystrudept
Surface (0–10 cm) soil properties		
pH (in water)	5.9 (0.30)†	6.9 (0.13)
Organic matter, % (w/w)‡	1.1 (0.14)	1.6 (0.05)
Mehlich 3 P, mg kg ⁻¹	88 (5.31)	98 (1.72)
Sand, %§	78	50
Silt, %	17	38
Clay, %	5	12

† Where multiple samples were measured, standard error is listed in parentheses ($n = 4$).

‡ Soil organic matter by loss-on-ignition.

§ Particle size analysis by the hydrometer method.

maintained weed free with herbicides. At BARC-SF, plots were 3 m wide by 15 m long, and at CMREC plots, were 6 m wide by 12 m long.

Site Management History

At CMREC, before the start of the experiment, a rotation of corn followed by winter wheat and double-crop soybean was grown from 2005 to 2006. The soybean crop was mowed at a vegetative stage in early August 2006 and left to decompose as a source of organic N to promote cover crop growth on the sandy soil at this site. When the soybean crop was mowed, the aboveground dry matter contained 56 kg N ha⁻¹ with a C/N ratio of 13. The field had been managed using no-till practices since the fall of 2003 when the field was last chisel plowed. During this time, no P fertilizers were applied to the soil.

At BARC-SF, before the start of the experiment, sweet corn and soybean were grown in 2004 and 2005, respectively. Following the soybean harvest in the fall of 2005, the field remained in weedy fallow until the cover crop experiment was planted in August 2006. The field had a long history of conventional tillage practices. In 2006, the field was moldboard plowed in May and disked in June and July before the start of the cover crop experiment in August. On 30 Aug. 2006, P and K fertilizers were broadcast applied at rates of 84 kg ha⁻¹ of K as KCl and 17 kg ha⁻¹ of P as triple superphosphate based on soil test recommendations. To ensure adequate cover crop growth, 62 kg ha⁻¹ of N as urea was also broadcast applied on 30 Aug. 2006.

Cover Crop Management

At all sites, the cover crop treatments were planted using a no-till drill with 16-cm row spacing. Rye was seeded at a rate of 135 kg ha⁻¹ and forage radish was seeded at a rate of 14 kg ha⁻¹. Before planting the cover crop treatments in 2007 and 2008, weeds were controlled with glyphosate [*N*-(phosphonomethyl)glycine] (1.85 L ha⁻¹ a.i.) and 22 kg N ha⁻¹ as a urea-NH₄NO₃ solution was applied as a starter fertilizer for the cover crops to ensure adequate growth. Cover crops were planted at CMREC on 12 Sept. 2006, 28 Aug. 2007, and 27 Aug. 2008 and at BARC-SF on 31 Aug. 2006, 27 Aug. 2007, and

28 Aug. 2008. Weeds in the no-cover-crop plots were controlled with glyphosate (1.85 L ha⁻¹ a.i.) on 18 Sept. 2007 at CMREC and 4 Oct. 2007 at BARC-SF and with paraquat dichloride (1,1'-dimethyl-4,4'-bipyridinium dichloride) (0.68 L ha⁻¹ a.i.) on 5 Nov. 2007 at BARC-SF. For all site-years, the forage radish cover crop was killed naturally when temperatures dropped below -4°C during January. The rye cover crops were killed when all plots were sprayed at CMREC with paraquat dichloride (0.68 L ha⁻¹ a.i.) and 2,4-D [(2,4-dichlorophenoxy)acetic acid] (1.05 L ha⁻¹ a.i.) on 10 Apr. 2007, 12 Apr. 2008, and 29 Apr. 2009 and at BARC-SF with glyphosate (1.85 L ha⁻¹ a.i.) on 10 Apr. 2007, 16 Apr. 2008, and 28 Apr. 2009.

Corn Management

Corn was grown in the summers of 2007 and 2008 and harvested for silage. Corn management was described in detail by White and Weil (2010). In brief, corn was planted with a no-till drill at CMREC on 23 Apr. 2007 and 16 Apr. 2008 and at BARC-SF on 24 Apr. 2007 and 7 May 2008. Nitrogen fertilizer was applied at planting (22 kg N ha⁻¹) and again at the V8 stage (112 kg N ha⁻¹). No other fertilizers were applied to the corn crop. Weeds were managed with herbicides. Corn was harvested for silage on 16 Aug. 2007 and 12 Aug. 2008.

Cover Crop Dry Matter Sampling

The shoots and fleshy taproots of the forage radish cover crop were sampled near the time of maximum dry matter accumulation but before killing frost in the late fall. The shoots of the rye cover crop were sampled in the spring before being killed by herbicides. Cover crop samples were obtained by removing plant parts from two 0.25-m² quadrats in each plot. In the first 2 yr of the experiment, both the shoots and the fleshy taproots of forage radish were sampled. Forage radish plants rooted within the quadrat were pulled from the soil by hand to collect the taproots. Roots and shoots were separated in the field. In the third year of the experiment, forage radish taproots were not sampled. For rye, only the shoots were sampled. All plant parts were washed to remove attached soil before drying in a forced-draft oven at 60°C for a

minimum of 7 d. Samples were weighed, then ground and sieved to <2-mm particle size, and stored in sealed polyethylene vials.

Plant Tissue Phosphorus Analysis

Plant tissue P concentration was determined by ashing 0.4 g of each tissue sample in a muffle furnace at 550°C for 5 h. The ash was dissolved in 40 mL of 0.3 mol L⁻¹ HCl and filtered through Whatman no. 42 filter paper (Whatman International, Maidstone, UK). The P concentration of the filtrate was measured colorimetrically using the vanadomolybdophosphoric acid method (Kuo, 1996) on a spectrophotometer set to 420 nm (DU720, Beckman-Coulter, Fullerton, CA).

Soil Sampling

Composite bulk soil samples were collected from each plot in the spring of 2007, 2008, and 2009. A 1.85-cm-diameter soil probe was used to collect cores from random locations within each plot. In 2007 and 2008, six cores were collected from each plot, whereas in 2009, 10 cores were collected from each plot. In the radish plots, a buffer zone within 5 cm of radish taproot holes was excluded from the bulk soil sampling procedure. The buffer distance of 5 cm around radish taproot holes was selected to establish a zone of soil where the influence of taproots on soil test P would be minimized while still maintaining a large enough area of soil from which to sample to obtain a sample representative of the bulk soil in the plot. At CMREC, bulk soil samples were collected on 24 Apr. 2007, 15 May 2008, and 16 Apr. 2009. At BARC-SF, bulk soil samples were collected on 5 Apr. 2007, 15 May 2008, and 23 Apr. 2009. Each core was divided into depth segments of 0 to 2.5, 2.5 to 10, and 10 to 20 cm. The cores from each plot were pooled to create a composite sample of each depth range. Soil samples were stored under refrigeration in sealed bags for <24 h before being air dried. After drying, soil

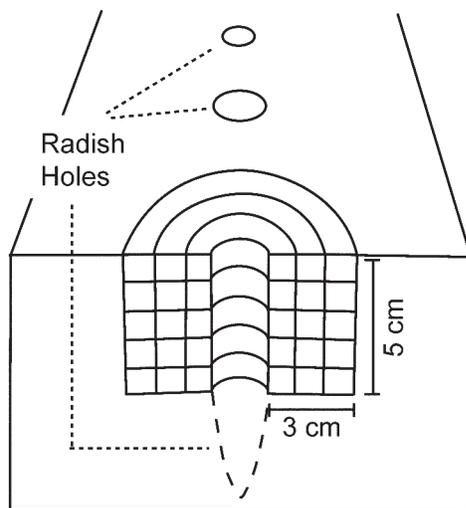


Fig. 2. A cross-section of the small-scale soil sampling conducted around the perimeter of individual radish holes in the spring at the Central Maryland Research and Education Center (CMREC) in 2009 and the Beltsville Agricultural Research Center South Farm (BARC-SF) in 2008. Soil was sampled in 1-cm-wide by 1-cm-deep increments around the perimeter of radish taproot holes, extending 3 cm from the edge of the taproot hole and 5 cm from the surface of the soil. One taproot hole was sampled in such a manner from three of the forage radish plots at each site.

samples were crushed and sieved through a 2-mm screen and stored in sealed polyethylene vials.

In 2009, the soil at the bottom of radish taproot holes was sampled. First, the depth to the bottom of the taproot hole was measured from the soil surface by resting a pencil on the bottom of the hole and marking the level of the soil surface on the pencil. The average hole depth was 6.5 cm at both sites. Then, a 1.85-cm-diameter soil probe was inserted into the radish hole and pushed into the soil at the bottom of the hole. The soil core was extracted and separated into two depth ranges: 0 to 2.5 and 2.5 to 5 cm, measured from where the soil began at the bottom of the hole. Six radish holes in each plot were sampled in this manner, and the cores within a plot were pooled to create composite samples by depth.

Small-scale soil sampling was conducted around the perimeter of an individual forage radish taproot hole in three radish plots in each experiment on 8 May 2008 at BARC-SF and on 16 Apr. 2009 at CMREC. Soil samples were collected by carefully removing the soil from around the circumference of the root holes in 1-cm-wide by 1-cm-deep sections using a stainless steel spatula (Fig. 2). The 1-cm-wide by 1-cm-deep sections were obtained to a depth of 5 cm from the surface and to a width of 3 cm from the outer edge of the root hole. These soil samples were air dried immediately, then crushed, sieved through a 2-mm screen, and stored in sealed polyethylene vials.

Soil Phosphorus Analysis

Mehlich 3 soil test P was selected as the method to measure soil P because it is widely used in soil fertility studies as a predictor of plant-available P and in environmental studies as a predictor of water-soluble P, desorbable P (Fe oxide strip P), and total sorbed P (oxalate P) (Sims et al., 2002). Soil samples were analyzed for Mehlich 3 extractable P (Mehlich, 1984; Sims, 2000) using 2 g of soil and 20 mL of extracting solution. The extracting solution was filtered through Whatman no. 42 filter paper. The P concentration in the extracting solution was measured colorimetrically using the ascorbic acid method (Kuo, 1996) on a spectrophotometer set to 880 nm (DU720, Beckman-Coulter).

Statistical Analysis

Cover crop dry matter, tissue P concentration, and P uptake data were analyzed by ANOVA in the Mixed procedure of SAS (SAS Institute, Cary, NC). To maximize the power of the analysis, data from all sites and years were pooled in the ANOVA. Sites and blocks were considered random factors and cover crop and year were considered fixed factors. Year was treated in the experimental design as a repeated measure within cover crop main plots. Compound symmetry was selected as the appropriate covariance structure for the repeated measurement using Akaike's information criterion. When the ANOVA indicated a statistically significant treatment effect ($P < 0.05$), mean comparisons were made using Fisher's LSD test.

Mehlich 3 soil test P data from bulk soil cores were also analyzed by ANOVA in the Mixed procedure of SAS, but site-years were analyzed separately to reduce the number of interactions in the model. Soil depth was treated as a repeated measure within cover crop main plots. Compound symmetry was selected as the appropriate covariance structure for the repeated measurement using Akaike's information criterion. When the

ANOVA indicated a statistically significant cover crop effect ($P < 0.05$), mean comparisons were made using Fisher's LSD test.

Mehlich 3 soil test P data from the small-scale radish root hole sampling were analyzed by ANOVA in the Mixed procedure of SAS. Each of the three radish root holes was treated as a replicate in the experimental design. The position of each sample point in relation to the soil surface and the wall of the root hole was treated as a repeated measurement within a radish hole replicate. Spatial autocorrelation among sampling positions around the radish hole was addressed by using an anisotropic exponential spatial covariance structure for the repeated measurement in the ANOVA. Mean values from each sampling point around the radish hole were compared with two control values using Dunnett's test. One control was the soil test P value of the no-cover-crop plots and the other control was the soil test P value of the bulk soil in radish plots between the radish rows.

RESULTS

Cover Crop Dry Matter and Phosphorus Content

Dry matter production of the cover crops varied among sites and between years (Tables 2 and 3). At CMREC, forage radish shoots produced greater dry matter than rye shoots in 2008 and 2009 and an equivalent amount of dry matter as rye in 2007. At BARC-SF, forage radish produced less dry matter than rye in 2007 and 2009 and an equivalent amount of dry matter as rye in 2008. The fleshy portion of forage radish taproots that could be pulled up by hand contained around 1000 kg ha⁻¹ dry matter in the years when they were sampled.

Tissue P concentrations also varied among sites and between years (Table 2). Radish shoot P concentration was greater than rye shoot P concentration at all sites and years (Table 3). The P concentration of the radish roots was sometimes greater than, sometimes less than, and sometimes the same as the P concentration of radish shoots.

Total P uptake by cover crops is influenced by both the tissue P concentration and the total dry matter accumulation. In this study, however, total P uptake was more closely associated with dry matter production of the cover crops ($r = 0.84$) than with tissue P concentrations ($r = 0.49$). Despite the lower shoot P concentration of rye compared with radish, in cases where rye accumulated >6000 kg ha⁻¹, such as at BARC-SF in 2007 and 2009, total P uptake by rye shoots was equivalent to or greater than P uptake by radish shoots (Table 3).

Soil Test Phosphorus of Bulk Soil

After the first year of cover crops (2007), there was no cover crop effect on bulk soil test P at CMREC (Table 4). Following the second (2008) and third (2009) years of cover cropping,

Table 2. Significance of year, site, and cover crop effects on cover crop dry matter, cover crop tissue P concentration, and cover crop P uptake. Forage radish and cereal rye cover crops were planted in the fall of 2006, 2007, and 2008 at two sites. Forage radish biomass was sampled in the fall of each year near the time of maximum dry matter accumulation. Cereal rye biomass was sampled in the spring, before termination with herbicides. All site years were pooled into a single ANOVA.

Source of variation	df	$P < F$		
		Dry matter	Tissue P conc.	P uptake
Cover	42	<0.0001	<0.0001	<0.0001
Site × cover	42	<0.0001	<0.0001	<0.0001
Year	42	0.0236	0.0002	0.0741
Year × cover	42	<0.0001	<0.0001	<0.0001
Year × site	42	0.0001	<0.0001	0.3152
Year × site × cover	42	0.0001	<0.0001	0.0248

however, there were significant cover crop × depth interactions on soil test P. After the third year of cover cropping, rye had decreased soil test P compared with no cover crop in the 0- to 10-cm depth range (Fig. 3). Forage radish had decreased soil test P in the 2.5- to 10-cm depth range compared with no cover crop. At the 10- to 20-cm depth range, there were no differences among

Table 3. Cover crop dry matter production, tissue P concentration, and P uptake measured for forage radish in fall and for rye in spring at the Central Maryland Research and Education Center (CMREC) and Beltsville Agricultural Research Center South Farm (BARC-SF) experimental sites during 3 yr. Forage radish and cereal rye cover crops were planted in the fall of 2006, 2007, and 2008 at two sites. Forage radish biomass was sampled in the fall each year near the time of maximum dry matter accumulation. Cereal rye biomass was sampled in the spring, before termination with herbicides.

Forage plant part	Dry matter	P conc.	P uptake	Planting date	Sampling date
	kg ha ⁻¹	g P kg ⁻¹	kg P ha ⁻¹		
CMREC 2007					
Radish root	1157 a†	6.1 c	7.0 b	12 Sept. 2006	15 Nov. 2006
Radish shoot	1306 ab	4.5 b	5.9 b	12 Sept. 2006	15 Nov. 2006
Rye shoot	1711 b	1.8 a	3.0 a	12 Sept. 2006	1 Apr. 2007
CMREC 2008					
Radish root	1084 a	4.1 b	4.5 a	28 Aug. 2007	9 Nov. 2007
Radish shoot	2629 c	5.4 c	14 b	28 Aug. 2007	9 Nov. 2007
Rye shoot	1546 b	2.1 a	3.3 a	28 Aug. 2007	7 Mar. 2008
CMREC 2009					
Radish root	–	–	–	–	–
Radish shoot	2892 b	3.5 b	10 b	27 Aug. 2008	31 Oct. 2008
Rye shoot	1914 a	2.3 a	4.4 a	27 Aug. 2008	7 Apr. 2009
BARC-SF 2007					
Radish root	936a	3.8 ab	3.6 a	31 Aug. 2006	15 Nov. 2006
Radish shoot	4282 b	4.1 b	18 b	31 Aug. 2006	15 Nov. 2006
Rye shoot	7345 c	3.4 a	25 c	31 Aug. 2006	1 Apr. 2007
BARC-SF 2008					
Radish root	1235 a	4.1 a	5.0 a	27 Aug. 2007	09 Nov. 2007
Radish shoot	4026 b	6.3 b	25 c	27 Aug. 2007	09 Nov. 2007
Rye shoot	4117 b	3.9 a	16 b	27 Aug. 2007	7 Mar. 2008
BARC-SF 2009					
Radish root	–	–	–	–	–
Radish shoot	3619 a	6.1 b	22 a	28 Aug. 2008	31 Oct. 2008
Rye shoot	6295 b	4.0 a	26 a	28 Aug. 2008	7 Apr. 2009

† Within site and year, means followed by different letters are significantly different ($P < 0.05$, F -protected LSD)

Table 4. Significance of cover crop and depth effects on bulk soil Mehlich 3 soil test P at the Central Maryland Research and Education Center (CMREC) and Beltsville Agricultural Research Center South Farm (BARC-SF) experimental sites. Soil samples were collected in the spring following termination of the cover crops. In forage radish plots, bulk soil samples were collected from between the rows where forage radish had been planted and not within 5 cm of a taproot hole. In the rye and no-cover-crop plots, bulk soil samples were collected from random locations within each plot.

Source of variation	df	<i>P</i> > <i>F</i>					
		CMREC			BARC-SF		
		2007	2008	2009	2007	2008	2009
Cover	6	0.6985	0.1884	0.1075	0.1612	0.2336	0.1955
Depth	18	<0.0001	<0.0001	<0.0001	<0.0001	0.0449	<0.0001
Cover × depth	18	0.5597	0.0029	0.0019	0.0895	0.2110	<0.0001

the three cover crop treatments. In all years, there was a general trend with depth, where soil test P was lower at shallower depths.

At BARC-SF, there were no cover crop effects on bulk soil test P until after the third year (2009) of cover cropping, when there was a significant cover crop × depth interaction (Table 4). After the third year of cover cropping, forage radish had increased soil test P at the 0- to 2.5-cm depth compared with both the rye cover crop and no cover crop (Fig. 4). There were no differences in bulk soil test P between cover crop treatments at the 2.5- to 20-cm depth.

Soil Test Phosphorus Surrounding Forage Radish Root Holes

At both CMREC and BARC-SF, Mehlich 3 soil test P values within 1 cm of forage radish holes were greater than the soil test P value in both the no-cover-crop treatment and the bulk soil from forage radish plots (Table 5). At BARC-SF, elevated soil test P surrounding root holes extended 3 cm away from the root hole and to a depth of 3 cm when compared with soil in the no-cover-crop treatment. At CMREC, however, elevated soil test P did not extend beyond 1 cm from the root hole.

Soil at the bottom of radish root holes also had elevated soil test P values compared with the bulk soil in the radish treatment (Table 6). At BARC-SF, elevated soil test P values extended 5 cm below the bottom of the root hole, whereas at CMREC, elevated soil test P levels only extended 2.5 cm below the root hole.

DISCUSSION

Cover Crop Phosphorus Content

Much of the variability in P uptake by cover crops among sites and years was due to differences in dry matter production. Both rye and forage radish generally produced less shoot dry matter at CMREC than at BARC-SF. This finding is probably due to N deficiency at CMREC, observed as chlorosis of the oldest leaves, that limited cover crop growth. The soil at CMREC is a coarser texture than at the other sites, which may have caused residual N to leach beyond the rooting zone of the cover crops more readily than at BARC-SF.

The soil at CMREC also had less organic matter than at BARC-SF, so it probably supplied less mineralized N during the growth of cover crops in the fall and spring.

In 2008, rye cover crops were sampled for dry matter production in early March, whereas in 2007 and 2009, sampling occurred in early April. The earlier sampling date in 2008 occurred before the rye's rapid spring growth, which accounted for the lower dry matter production measured for rye in that year.

We did not find any other studies reporting P uptake by forage radish cover crops in the literature; however, reports of P uptake of oilseed radish (*Raphanus sativus* L. var. *oleiferus*), a close relative of forage radish with similar characteristics, are similar to our P uptake findings (Brown et al., 2008; Wang et al., 2008). Brown et al. (2008) also found that P uptake by oilseed radish increased in response to P fertilizer applications. In our experiment, the soil test P values were in the optimum range for crop production. Many agricultural fields in the Mid-Atlantic United States, however, have excessive soil test P values that are five to 10 times greater than those in our experiment. Given the increased P uptake by oilseed radish resulting from the application of P fertilizer, the P uptake potential of forage radish in excessively high P soils may be greater than we found in this study.

The rapid and substantial P uptake by forage radish cover crops deserves consideration as a tool to remediate soil with excessive P concentrations. Harvesting a forage radish

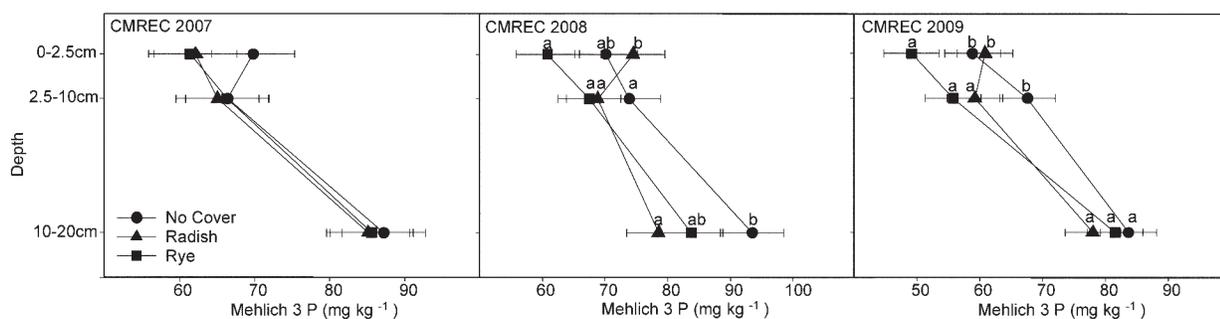


Fig. 3. Mehlich 3 soil test P of bulk soil at the Central Maryland Research and Education Center (CMREC) following each year of cover cropping. Soil samples were collected in the spring following termination of the cover crops. In forage radish plots, bulk soil samples were collected from between the rows where forage radish had been planted and not within 5 cm of a taproot hole. In the rye and no-cover-crop plots, bulk soil samples were collected from random locations within each plot. Bars indicate standard error of the means. Within year and depth range, means with different letters are significantly different (*P* < 0.05, *F*-protected LSD). Where no letters are indicated, the ANOVA did not detect any significant effects involving the cover crop.

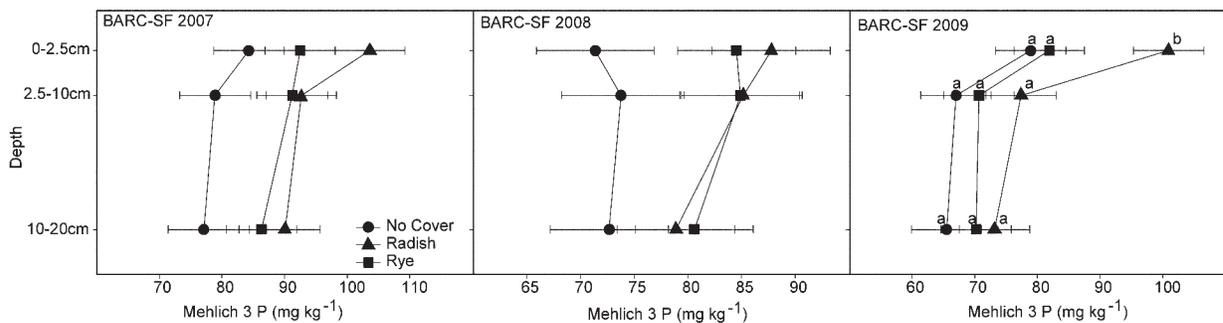


Fig. 4. Mehlich 3 soil test P of bulk soil at the Beltsville Agricultural Research Center South Farm (BARC-SF) following each year of cover cropping. Soil samples were collected in the spring following termination of the cover crops. In forage radish plots, bulk soil samples were collected from between the rows where radish had been planted and not within 5 cm of a taproot hole. In the rye and no-cover-crop plots, bulk soil samples were collected from random locations within each plot. Bars indicate standard error of the means. Within year and depth range, means with different letters are significantly different ($P < 0.05$, F -protected LSD). Where no letters are indicated, the ANOVA did not detect any significant effects involving the cover crop.

cover crop could decrease soil P by increasing crop P removal rates. Brown (2006) reported that after 3 yr of planting and harvesting a winter cereal forage following corn silage in Idaho, soil test P declined 50% more compared with growing and harvesting only corn silage. In that study, winter cereal forage crops removed between 10 and 30 kg P ha⁻¹ annually, similar to the quantity of P we found forage radish and rye cover crops to accumulate.

Our findings suggest that for the purpose of P removal, cover crops should be managed to achieve maximum dry matter production. This result is similar to the findings of Eghball et al. (2003), who tested a number of corn hybrids and soybean cultivars for their P removal potential, and found that P removal in grain was linearly correlated with grain yield. In Maryland's climate, maximizing dry matter production for forage radish requires a planting date before 1 September and an adequate supply of available N (Weil et al., 2009). For rye, allowing its growth to continue as late into spring as possible will maximize dry matter production and may result in P removal rates as great as or greater than forage radish. Further research is warranted on using forage radish and other cover crops to remediate excessively high P soils.

Soil Test Phosphorus of Bulk Soil

The effect of cover crops on the soil test P of bulk soil (collected from not within 5 cm of a radish root hole) varied between cover crops, site, and soil depth. After 3 yr of cover crops at BARC-SF, soil test P increased at the 0- to 2.5-cm depth following forage radish but not after rye, even though each cover crop cycled similar quantities of P to the soil surface in their shoots. This result possibly occurred because the rye residue at the soil surface did not decompose as quickly as the forage radish residue, causing the P cycled by the rye to remain in an organic P fraction. The organic P fraction is not fully detected by the Mehlich 3 extract and ascorbic acid method of P measurement (Kuo, 1996).

Increased P concentrations at the soil surface is a recognized phenomenon when P-containing fertilizers are applied to the soil surface in no-till systems (Garcia et al., 2007; Mallarino

Table 5. Mehlich 3 soil test P of soil sampled around forage radish taproot holes at the Beltsville Agricultural Research Center South Farm (BARC-SF) in May 2008 and the Central Maryland Research and Education Center (CMREC) in May 2009. The sampling extended 5 cm in depth from the surface and in increments of 0 to 1, 1 to 2, and 2 to 3 cm horizontally from the wall of the root hole.

Depth cm	BARC-SF 2008			CMREC 2009		
	0–1 cm	1–2 cm	2–3 cm	0–1 cm	1–2 cm	2–3 cm
0–1	142 Aa†	142 Aa	137 Aa	78 Aa	65	61
1–2	140 Aa	125 Aa	123 Aa	81 Aa	66	63
2–3	133 Aa	114 A	108 A	87 Aa	66	60
3–4	121 Aa	104	98	104 Aa	74	60
4–5	115 A	98	95	99 Aa	73	56

† Within a site, means followed by an uppercase A are significantly different than the Mehlich 3 P of the 0–2.5-cm soil with no cover crop, which was 73 mg P kg⁻¹ at BARC-SF and 57 mg P kg⁻¹ at CMREC, while means followed by a lowercase a are significantly different than the Mehlich 3 P of the 0–2.5-cm radish bulk soil, which was 85 mg P kg⁻¹ at BARC-SF and 58 mg P kg⁻¹ at CMREC ($P < 0.05$, Dunnett's test).

Table 6. Mehlich 3 soil test P of soil in forage radish plots sampled from the bulk soil between radish rows and from soil at the bottom of the radish taproot holes at the Beltsville Agricultural Research Center South Farm (BARC-SF) in May 2008 and the Central Maryland Research and Education Center (CMREC) in spring of 2009.

Sampling location	Depth increment†	Mehlich 3 soil test P	
		CMREC	BARC-SF
Bulk soil‡	0–2.5	61 a§	101 b
	2.5–10	59 a	77 a
	10–20	78 ab	73 a
Root hole bottom¶	0–2.5	202 c	161 d
	2.5–5	110 b	124 c

† For bulk soil, soil depth was measured from the soil surface. For soil at the bottom of root holes, soil depth was measured from the bottom of the root hole. On average, the root holes were 6.5 cm deep at both sites, measured from the soil surface.

‡ The bulk soil samples were collected from between the rows where forage radish had been planted and not within 5 cm of a taproot hole.

§ Within a site, means followed by different letters are significantly different ($P < 0.05$, F -protected LSD).

¶ The soil from the bottom of radish root holes was a composite sample collected from 10 root holes in each plot, stratified to two depth segments: 0–2.5 and 2.5–5 cm measured from the bottom of the hole.

and Borges, 2006; Sharpley, 2003). We found that 3 yr of forage radish cover crops cycling P to the soil surface under no-till management resulted in a moderate increase in soil test P in the 0- to 2.5-cm depth at BARC-SF. The increase that did occur, however, was much less than has been observed to occur when P fertilizers are added to the surface.

At CMREC, neither forage radish nor rye cover crops resulted in elevated soil test P values at any depth of the bulk soil compared with the no-cover-crop control. At CMREC, P uptake by the cover crops was less than at BARC-SF due to low dry matter production. The decline in soil test P at the 0- to 10-cm depth following rye at CMREC may be a result of soil P being shifted into the organic P fraction associated with rye residues. The decline in soil test P at the 2.5- to 10-cm depth following forage radish may be due to the translocation of P by forage radish from the bulk soil to the surface soil and the soil immediately surrounding root holes. At CMREC, the trend toward decreased soil test P at shallower depths is probably because no P fertilizer had been applied to the field since the commencement of no-till practices and, with time, crop roots have removed greater quantities of P at the shallower soil depths.

Soil Test Phosphorus Surrounding Forage Radish Root Holes

The results of the intensive soil sampling around radish root holes indicate that the soil immediately surrounding forage radish root holes had greater soil test P values than either the soil that had not had a forage radish cover crop or the bulk soil between radish rows. We speculate that several mechanisms could contribute to the increase in soil test P surrounding taproot holes. One mechanism is that through biological and physical processes, P could be concentrated from the bulk soil into the soil surrounding taproot holes. This process would begin with the accumulation of bulk soil P in forage radish shoot and taproot biomass. When forage radishes winterkill and the residues decompose, P contained in the taproots would be released into the taproot holes where it becomes adsorbed to the soil surrounding the holes. Rainfall runoff may also dissolve P from decomposing shoots on the soil surface. This P-laden runoff may preferentially infiltrate into taproot holes, where the dissolved P would become adsorbed to the soil surrounding the root hole.

Another mechanism that may contribute to the increase in soil test P surrounding the root hole is the probable exudation of organic acids by forage radish roots. Other Brassicaceae members have been observed to increase soil P availability with organic acid root exudates (Hoffland et al., 1989; Shahbaz et al., 2006; Zhang et al., 1997). Decomposition of crop residues also releases organic acids and can increase soil P availability (Bah et al., 2003, 2006; Reddy et al., 2005).

In comparing the results between sites, soil within 1 cm of a radish hole had elevated soil test P values at both sites. Only at BARC-SF, however, were soil test P values elevated at the soil surface when measured up to 3 cm away from the radish hole and

in the bulk soil sampled between the radish rows. The patterns of P enrichment may have differed between sites because radish shoots did not cycle as much P to the surface at CMREC as they did at BARC-SF; however, radish roots contained a similar total amount of P at both sites.

Potential Implications of Soil Test Phosphorus Heterogeneity on Environmental Quality, Soil Sampling Methodology, and Soil Fertility

The heterogeneity in soil test P resulting from P cycling by forage radish cover crops has several potential implications for P loss to the environment, soil sampling methodology, and soil fertility. At BARC-SF, where forage radish accumulated substantial quantities of P, soil test P values were elevated at the soil surface and in the root holes. The increase in soil test P of the bulk soil between radish rows, however, did not exceed the threshold of 150 mg P kg⁻¹ where soils are considered to present a risk of environmental P pollution (Sims et al., 2002). Soil sampled from the vicinity of forage radish root holes, however, had soil test P values as high as 142 mg P kg⁻¹ in 2008 and 161 mg P kg⁻¹ in 2009, values near to and above the environmental risk threshold. At CMREC, where forage radish cycled smaller amounts of P, soil test P at the bottom of the root hole still dramatically increased to 202 mg P kg⁻¹, well above the environmental risk threshold. It is unknown how the small-scale spatial variability in soil test P that we observed may influence the risk of P loss to the environment from these fields.

At both sites, the increases in soil test P near to and above the environmental risk threshold would not have been detected if soil sampling were restricted to the areas away from root holes. Soil sampling protocols often specify avoiding areas of soil that are known to be abnormal, as some might consider a radish root hole to be. The area within 3 cm of a radish hole can account for a large portion of a field, however. Recommended seeding rates of forage radish often result in approximately 80 radish root holes per square meter. Assuming the radius of a radish hole to be 2 cm, the area within 3 cm of the wall of a radish hole will account for about 60% of the field $[(5 \text{ cm} \times 5 \text{ cm} \times 3.14 \times 80)/(100 \text{ cm} \times 100 \text{ cm}) = 0.628]$. Others have observed heterogeneity in soil test P following banded applications of P fertilizer and recommended a modified soil sampling procedure (Duiker and Beegle, 2006; Mallarino and Borges, 2006). Further research is necessary to determine if soil sampling procedures should be modified when sampling a field after a forage radish cover crop has been grown.

The P cycling characteristics of forage radishes may also suggest a method to increase P availability in P-deficient soils. In P-deficient soil, existing soil P is often relatively unavailable because of sorption to soil particles. Forage radish cover crops may be able to alleviate this problem by acquiring diffuse soil P and concentrating it in the soil surrounding root holes. By concentrating the soil P in distinct zones, P availability increases because the P sorption capacity of the soil is filled to a greater extent and P is more readily released into the soil solution

where the P can be taken up by plant roots. Through a similar mechanism, banded applications of P fertilizers have been shown to increase P availability to crops compared with broadcast applications (Elhamdi and Woodard, 1995; Prummel, 1957; Sander et al., 1990). Forage radish cover crops should be further investigated for their potential to biologically band the existing soil P in P-deficient soils.

Despite the observed increase in soil test P surrounding root holes in our study, corn following forage radish did not have greater tissue P concentrations than corn following no cover crop (White and Weil, 2010), and no correlations were found between soil test P and crop growth or yield (data not shown). This result probably occurred because soil test P was already in the optimal range for crop growth when the study was initiated. We suggest that further research be conducted in P-deficient soils to determine the ability of forage radish cover crops to increase P availability.

CONCLUSIONS

We found that shoots of both forage radish and rye cover crops have the potential to take up significant quantities of P when these cover crops are managed for maximum dry matter production. Further research should be conducted to determine if harvesting forage radish cover crops can remediate excessively high P soil by increasing P removal rates.

We also found that after 3 yr of forage radish cover crops managed with no-till practices, soil test P of the surface soil moderately increased at the site where forage radish cycled large quantities of P. In the vicinity of forage radish root holes, however, soil test P increased dramatically at both sites, even when the total P cycled by the forage radish cover crops was small. We speculate that the increase in soil test P surrounding forage radish root holes could be a result of biological, physical, and chemical interactions among plants, the soil, and the environment that concentrate P in the soil surrounding root holes. Future research should investigate how the increases in soil test P surrounding root holes affects environmental P management in high-P soils and P fertility management in low-P soils.

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